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Report of Investigations 4957

THERMAL REQUIREMENTS FOR THE GASIFICATION OF LIGNITE IN AN EXTERNALLY HEATED RETORT

BY M. H. CHETRICK

United States Department of the Interior—March 1953

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UNITED STATES DEPARTMENT OF THE INTERIOR
Douglas McKay, Secretary
BUREAU OF MINES
J. J. Forbes, Director

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M. H. Chetrick[1/]

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INTRODUCTION

An important factor in the design and operation of a lignite-gasification plant is knowledge of the thermal requirements. These not only vary with different-size plants but also with the operating conditions for a plant of given capacity.

Thermal data have been collected since 1945 from a commercial-scale lignite-gasification pilot plant operated by the Bureau of Mines at Grand Forks, N. Dak. The description and operation of this plant and a study of the gas-composition data have already been described in previous reports (1, 2, 3, 4, 5).2/ This investigation was made to review the thermal data taken in tests and to correlate them in terms of the fraction of undecomposed steam and the H_2:CO ratio.

ACKNOWLEDGMENTS

The cooperation of the North Dakota Research Foundation for making available part of the funds for carrying out this study is acknowledged.

SUMMARY OF RESULTS

The following results were indicated by this investigation: (1) Based on net heating values of the gas, the heat requirements, ΔH_D, in B.t.u. per standard cubic foot of dry gas produced, vary with the H_2-CO ratio and may be represented by the following empirical equation:

$$\Delta H_D = \frac{148}{(H_2:CO)^{0.135}}$$

As indicated by this equation, the heat requirements vary only moderately with the H_2-CO ratio. Under the prevailing operating conditions this variation ranges from approximately 135 to 107 B.t.u. between the minimum and maximum H_2-CO ratios of 2 and 9, respectively. (2) The cold thermal efficiency of the gasification unit, based on gross heating values, ranges between 45 and 65 percent under the prevailing operating conditions, decreasing with increasing fraction of undecomposed steam. These figures, however, do not include the potential heat of the char, which is not utilized in the pilot plant at the present time. If the char were effectively utilized and included as useful heat, the maximum efficiency would be raised to approximately 80 percent.

ANALYSIS AND CORRELATION OF DATA

Heat Requirements

The H_2-CO ratio often is used as a basis for expressing the composition of the gas produced. This ratio, which is controlled by the operating variables in a gasification plant, also determines the amount of heat required to produce a given volume of gas.

2/ Underlined numbers in parentheses refer to citations at the end of the text.

For the same volume of wet gas[3] produced, the heat requirements should increase with decreasing H_2-CO ratios. This is illustrated in table 1 for H_2-CO ratios of 2, 5, and 9, using as a basis 1,000 std. cu. ft. of wet gas produced. (Std. cu. ft. = One cubic foot measured at 60° F. and 30 in. Hg.)

TABLE 1. - Selected data per 1,000 std. cu. ft. wet gas produced

H_2-CO ratio	2	5	9
Wet gas produced........std. cu. ft.	1,000	1,000	1,000
Dry gas produced........std. cu. ft.	835	533	350
Undecomposed H_2O........std. cu. ft.	165	467	650
Natural lignite charged........lb.	45.9	21.9	14.1
Steam injected........lb.	7.0	26.3	34.1
H_2O equivalent of O_2 in lignite........lb.	22.8	10.9	7.0
Total equivalent H_2O charged........lb.	29.8	37.2	41.1
Carbon gasified........lb.	11.8	6.7	4.3
H_2O decomposed........lb.	21.9	14.9	10.1
Heat supplied by heating gas........B.t.u.	115	63	39

The above figures were calculated from correlation presented in a previous report (2). It is seen that the heat requirements should increase with decreasing H_2-CO ratios, owing to the greater quantities of steam and carbon that react in the endothermic water-gas reactions, the larger quantity of natural lignite charged that must be heated up to its reaction temperature after entering the retort, and the larger quantity of water that must be vaporized from the lignite.

A summary of the pertinent data from the pilot plant along with calculated heat requirements for the various H_2-CO ratios are given in table 2. A continuous annulus was employed in runs 7 and 8, and a divided annulus in the remainder of the runs.

It has been shown in a previous report (2) that the fraction of undecomposed steam in the gas produced is related to the H_2-CO ratio and offers a convenient basis for correlating gasification data. The fraction of undecomposed steam is defined as the ratio of the moles of undecomposed H_2O in the gas to the total moles of entering H_2O.

Using as a basis 1 std. cu. ft. of wet gas produced, a straight line results when the net B.t.u. of gas burned directly to supply heat to the process are plotted against the fraction of undecomposed steam. This relationship is illustrated by figure 1. The heat requirements are seen to decrease with increasing fractions of undecomposed steam, approaching a value of zero at a fraction of undecomposed steam of one.

Figure 2 gives the relationship between the heat requirements and the H_2-CO ratio. The plotted points represent the data from table 2, and the solid curve represents a relationship derived from figure 1 and a correlation between the H_2-CO ratio and the fraction of undecomposed steam. The variation of the H_2-CO ratio with the fraction of undecomposed steam, presented in a previous report (2), may be expressed by the following empirical equation:

$$\text{Fraction undecomposed } H_2O = 1 - \frac{1.27}{(H_2:CO)^{0.725}}. \qquad \text{(A)}$$

3/ Wet gas, as used in this report, refers to the total volume of products and is defined as the sum of uncondensable gases and undecomposed steam.

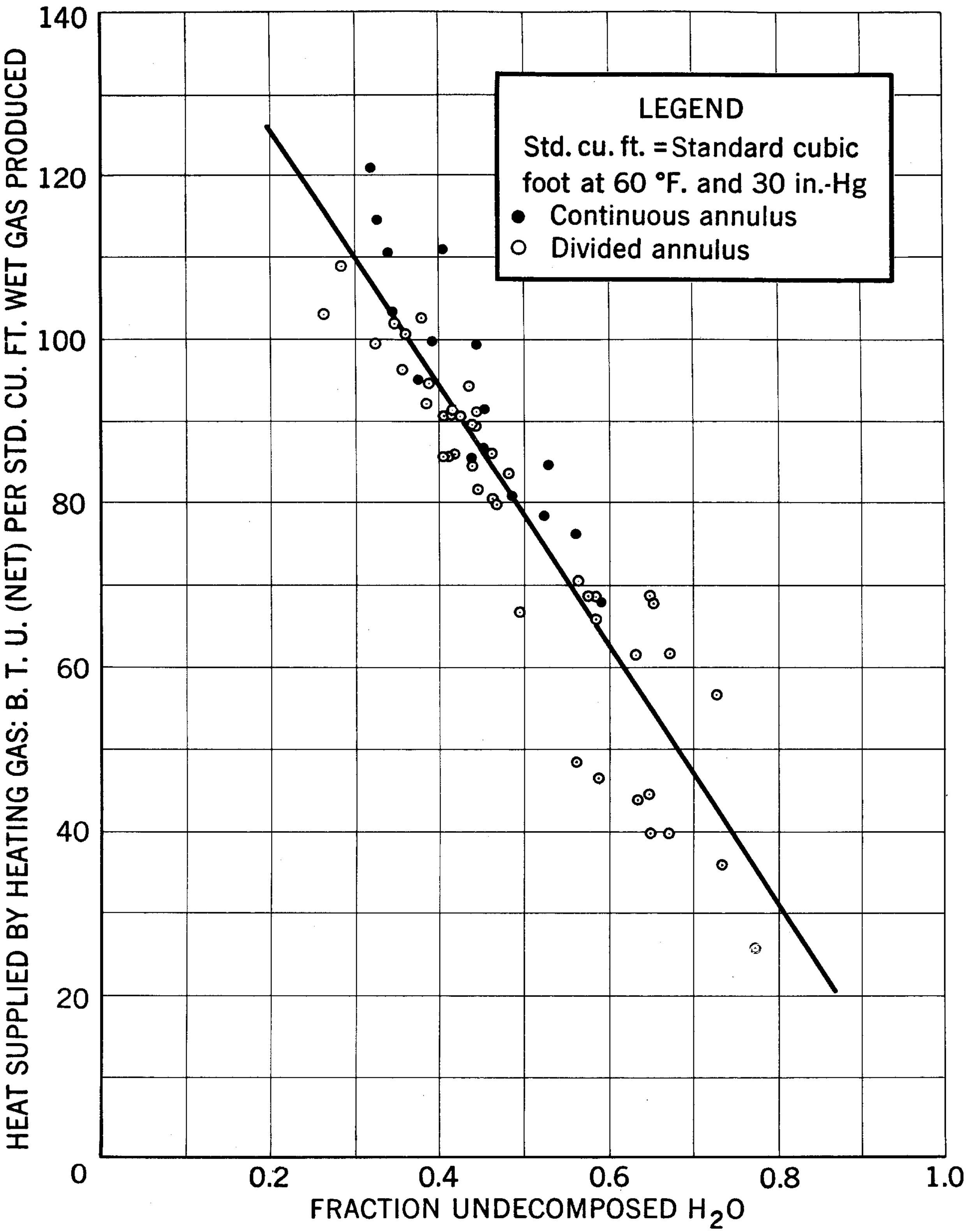

Figure 1. - Effect of undecomposed steam on heat requirements.

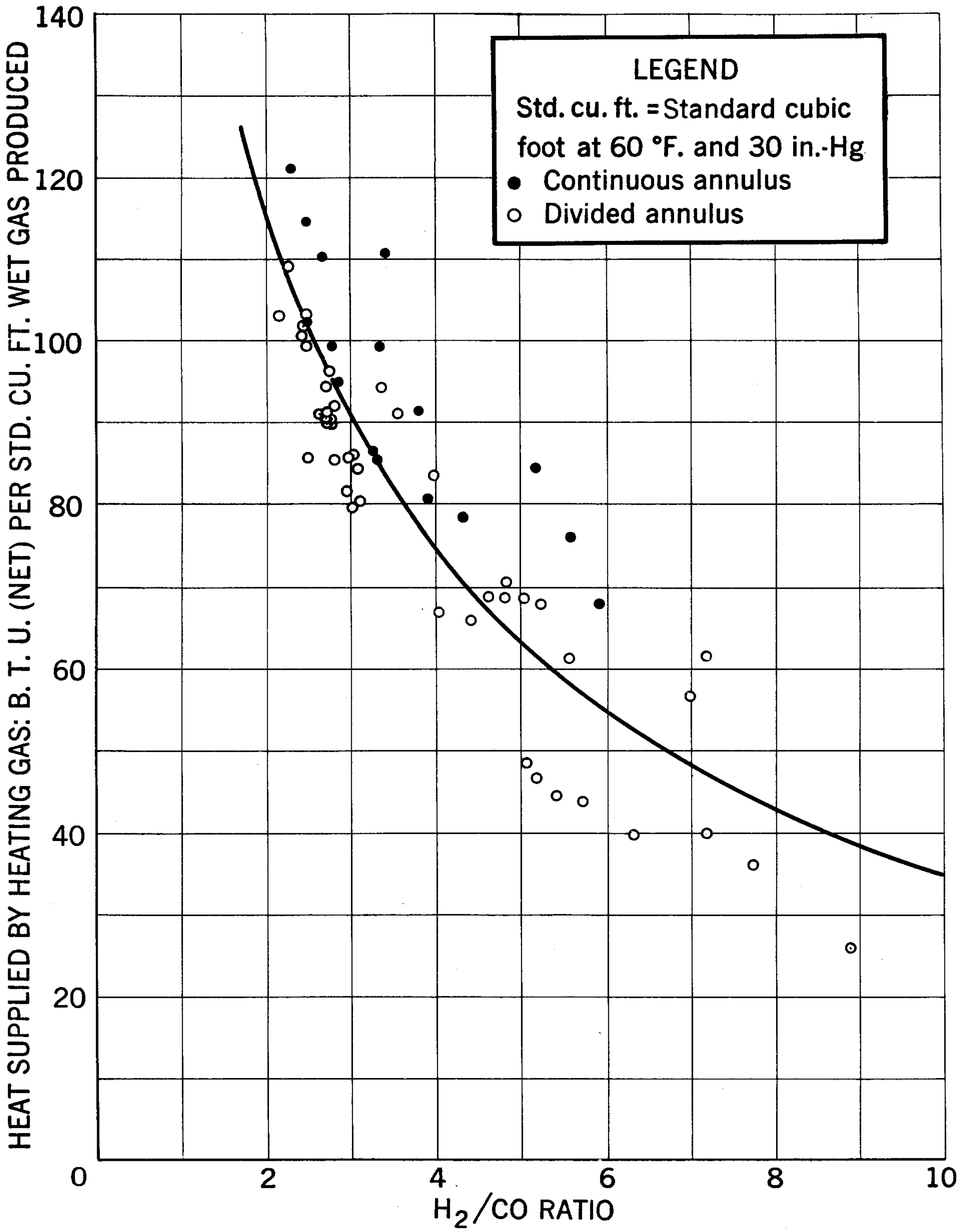

Figure 2. - Effect of H_2-CO ratio on heat requirements.

TABLE 2. - Summary of heat requirements from lignite-gasification pilot plant[1/]

(1) Run No.	(2) H_2-CO ratio	(3) Fraction undecomposed H_2O	(4) Volume dry gas produced, M std.cu.ft./hr.	(5) Volume undecomposed steam in gas, M std.cu.ft./hr.	(6) Total volume wet gas produced, M std.cu.ft./hr.	(7) Heat supplied by heating gas: M B.t.u. (net)/hr.	(8) Heat supplied by heating gas: B.t.u. (net)/ std.cu.ft. wet gas	(9) Gas offtake temp., °F.
3B	2.71	0.405	14.72	5.59	20.31	1,843	90.7	1,248
3D	2.96	.446	12.50	5.72	18.22	1,488	81.7	1,213
3F	2.48	.324	11.83	3.17	15.00	1,493	99.5	1,237
3G	2.18	.265	11.77	2.30	14.07	1,450	103.1	1,247
3H	2.43	.361	12.14	3.77	15.91	1,606	100.9	1,229
4B	2.50	.419	12.99	5.47	18.46	1,586	85.9	1,194
4C	2.82	.405	13.43	5.10	18.53	1,586	85.6	1,208
4D	2.97	.407	12.90	4.98	17.88	1,536	85.9	1,200
4E	2.79	.425	13.46	5.59	19.05	1,726	90.6	1,176
4F	2.71	.415	12.07	4.63	16.70	1,523	91.2	1,207
4G	2.75	.439	11.33	4.87	16.20	1,453	89.7	1,204
4H	3.08	.439	13.78	5.84	19.62	1,654	84.3	1,216
4I	2.49	.379	11.06	3.67	14.73	1,509	102.4	1,247
4J	2.82	.387	12.12	4.20	16.32	1,504	92.2	1,244
4K	2.45	.348	11.07	3.20	14.27	1,454	101.9	1,245
4L	2.63	.414	12.85	5.10	17.95	1,635	91.1	1,257
4M	3.02	.469	13.78	6.94	20.72	1,654	79.8	1,207
4N	3.11	.463	13.85	6.83	20.68	1,664	80.5	1,217
5A	5.25	.653	6.77	7.52	14.29	970	67.9	1,090
5B	7.21	.674	7.65	9.16	16.81	1,033	61.5	1,117
5C	7.02	.730	6.96	11.16	18.12	1,026	56.6	1,108
5D	5.05	.650	7.05	7.77	14.82	1,017	68.6	1,112
6A	4.04	.497	6.99	3.96	10.95	732	66.8	1,202
6B	5.20	.589	9.51	7.94	17.45	809	46.4	1,189
6C	5.07	.563	11.07	8.27	19.34	935	48.3	1,192
6D	5.42	.650	11.69	12.92	24.61	1,089	44.3	1,157
6E	5.73	.635	10.99	11.25	22.24	974	43.8	1,154
6F	6.34	.652	10.07	11.14	21.21	843	39.7	1,143
6G	7.76	.736	8.93	13.25	22.18	797	35.9	1,130
6H	8.99	.776	8.90	18.63	27.53	705	25.6	1,120
6I	7.19	.673	7.26	8.90	16.16	641	39.7	1,148
7A	3.35	.444	6.78	2.95	9.73	966	99.3	1,212
7B	3.82	.451	8.51	3.87	12.38	1,133	91.5	1,197
7C	3.91	.485	10.45	5.50	15.95	1,289	80.8	1,201
7D	4.31	.524	9.42	5.90	15.32	1,200	78.3	1,177
7E	5.59	.562	7.79	5.69	13.48	1,026	76.1	1,176
7F	5.18	.529	6.49	4.10	10.59	894	84.4	1,177
7G	5.95	.592	8.81	7.36	16.17	1,098	67.9	1,160
7H	3.43	.403	6.92	2.52	9.44	1,045	110.7	1,202
8A	2.66	.338	7.07	1.94	9.01	994	110.3	1,223
8B	2.49	.326	6.56	1.66	8.22	942	114.6	1,242
8C	2.87	.377	8.71	2.85	11.56	1,098	95.0	1,220
8D	3.32	.438	10.36	4.45	14.81	1,265	85.4	1,220
8E	2.30	.319	7.26	1.74	9.00	1,089	121.0	1,253
8F	2.78	.391	8.41	2.93	11.34	1,129	99.6	1,257
8G	3.28	.451	9.46	4.34	13.80	1,194	86.5	1,233
8H	2.49	.344	10.22	2.88	13.11	1,354	103.3	1,265
11A	3.04	.462	12.39	5.80	18.19	1,564	86.0	1,153
11C	2.75	.357	11.46	3.32	14.78	1,423	96.3	1,193
11D	2.30	.286	9.89	2.03	11.92	1,298	108.9	1,202
11E	2.73	.389	10.65	3.67	14.32	1,355	94.6	1,200
11F	4.82	.577	10.07	7.84	17.91	1,230	68.7	1,135
11G	4.84	.565	10.06	7.52	17.58	1,239	70.5	1,123
11H	4.63	.587	10.94	8.81	19.75	1,358	68.8	1,109
11I	4.40	.587	12.61	10.37	22.98	1,514	65.9	1,119
11J	3.38	.436	7.67	3.27	10.94	1,031	94.2	1,218
11K	3.57	.445	8.32	3.68	12.00	1,093	91.1	1,184
11L	3.99	.483	8.99	4.70	13.69	1,144	83.6	1,145
11M	5.59	.632	10.42	10.34	20.76	1,272	61.3	1,136

1/ Calculated from literature reference (1, 3, 4).
Std. cu. ft. = One cubic foot measured at 60° F. and 30 in. Hg.

As the composition of the gas produced in a gasification plant usually is expressed in terms of the H_2-CO ratio rather than the fraction of undecomposed steam, figure 2 possibly has a more practical significance than figure 1. However, the content of figure 1 permits the curve of figure 2 to be drawn with reasonable precision.

The curve in figure 2, relating the heat requirements and the H_2-CO ratio, may also be expressed by the following empirical equation over the experimental range investigated:

$$\Delta H_W = \frac{200}{(H_2:CO)^{0.725}}, \qquad (B)$$

where ΔH_W is the net B.t.u. required per standard cubic foot of wet gas produced.

It is often more convenient from an operational viewpoint to express the thermal requirements in terms of the dry gas produced rather than of the wet gas. Using a dry basis, the variation of the heat requirements with the H_2-CO ratio may be expressed by the following equation:

$$\Delta H_D = \frac{148}{(H_2:CO)^{0.135}}, \qquad (C)$$

where ΔH_D is the net B.t.u. required per standard cubic foot of dry gas produced. This equation was derived from equations (A) and (B), and a relationship was presented in a previous report (2) between the fraction of undecomposed steam with the percentage of dry gas in the wet gas produced.

Thermal Efficiency

The thermal efficiency of the process, which is defined as the percentage of the total heat input that can be effectively utilized, can be expressed in either of two ways, depending on whether or not the sensible heat in the gas produced can be used. As the gas leaving the retort is scrubbed and cooled, the sensible heat is lost in the scrubbing water. Therefore, the potential heat of the gas produced is the only useful heat, and the gas efficiency used is called the cold thermal efficiency.

In order to calculate the thermal efficiency of the gasification unit, heat balances were made for each run. A summary of the distribution of heat entering the gasification unit is shown in table 3. Columns (3), (4), and (5) give the magnitudes of the various items of heat entering. Column (6) is the sum of these items, giving the total heat entering the retort. The potential heat in the gas produced is given in column (7), and the cold thermal efficiency - the ratio of column (7) to column (6) - is given in column (8). All items are based on 1 hour and gross heating values above 60° F. A complete heat and material balance for a typical run is shown in table 4.

The thermal efficiency of the lignite-gasification pilot plant depends upon the operating variables employed. As it has been shown in a previous report (2) that the fraction of undecomposed steam can be taken as a single factor to combine the effects of all these variables, a relationship should exist between the fraction of undecomposed steam and the cold thermal efficiency. This relationship is illustrated by figure 3. It is seen that although the efficiency decreases with increasing fractions of undecomposed steam, the variation under the prevailing operating conditions ranges between 45 and 65 percent.

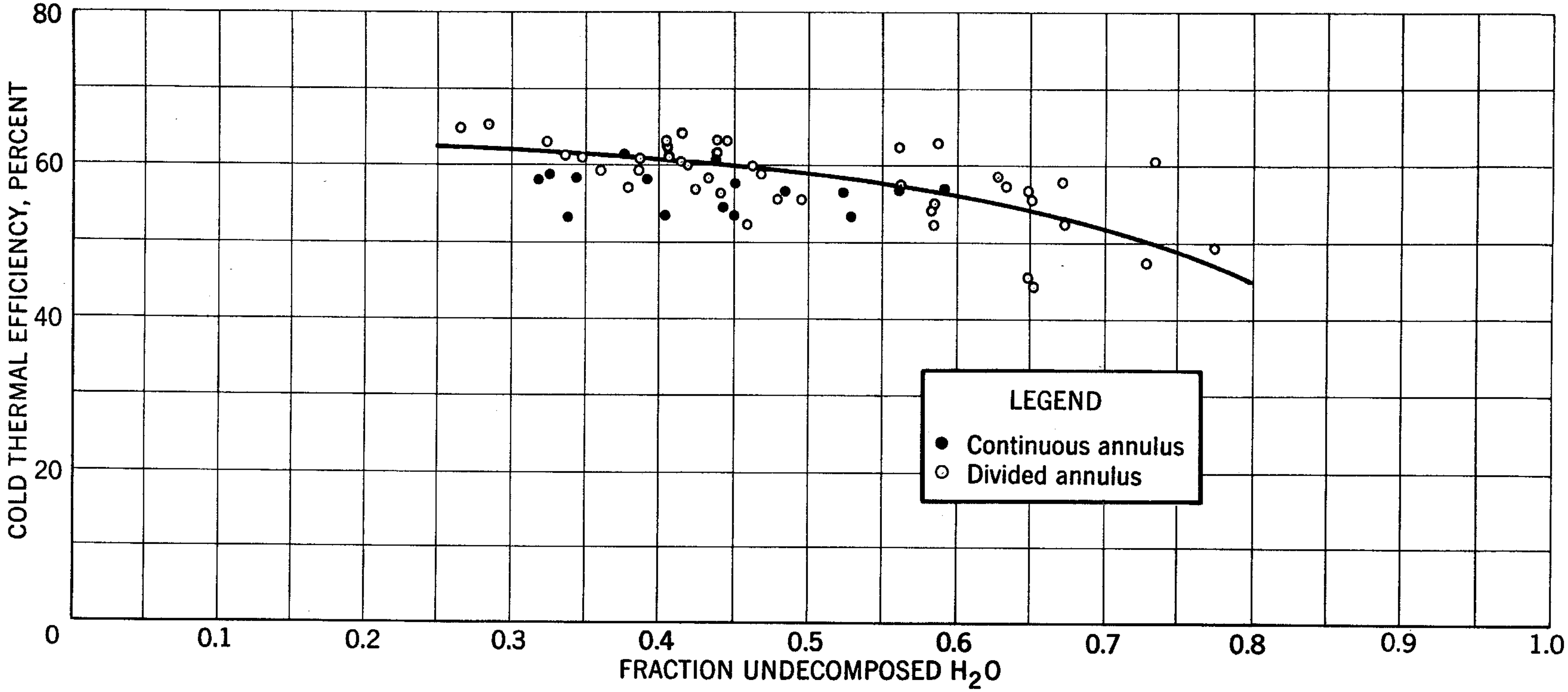

Figure 3. - Cold thermal efficiency vs. fraction undecomposed H_2O (based on gross heating values).

TABLE 3. - Summary of thermal efficiencies and distribution of heat entering lignite-gasification pilot plant[1/]

(Basis: 1 hr. gross heat above 60° F.)

(1) Run No.	(2) Fraction undecomposed H_2O	(3) Potential heat in lignite charged, M B.t.u.	(4) Total heat in process steam, M B.t.u.	(5) Potential heat in heating gas, M B.t.u.	(6) Total heat to retort, M B.t.u.[2/]	(7) Potential heat of gas produced, M B.t.u.	(8) $\frac{(7)}{(6)}$ 100 Cold thermal efficiency percent
3B	0.405	4,580	398	2,075	7,060	4,479	63.4
3D	.446	3,664	398	1,670	5,739	3,638	63.4
3F	.324	3,741	227	1,658	5,633	3,552	63.1
3G	.265	3,741	170	1,623	5,541	3,594	64.9
3H	.361	4,164	227	1,809	6,207	3,693	59.5
4B	.419	4,264	341	1,778	6,390	3,834	60.0
4C	.405	4,264	341	1,775	6,387	3,992	62.5
4D	.407	4,144	340	1,778	6,269	3,834	61.2
4E	.425	4,836	340	1,930	7,113	4,055	57.0
4F	.415	3,544	340	1,717	5,608	3,598	64.2
4G	.439	3,368	341	1,629	5,345	3,390	63.4
4H	.439	4,402	397	1,861	6,667	4,122	61.8
4I	.379	3,841	227	1,702	5,777	3,299	57.1
4J	.387	3,876	284	1,694	5,861	3,576	61.0
4K	.348	3,495	227	1,653	5,382	3,291	61.1
4L	.414	4,074	340	1,845	6,266	3,806	60.7
4M	.469	4,441	454	1,867	6,769	3,996	59.0
4N	.463	4,363	454	1,872	6,696	4,019	60.0
5A	.653	2,645	432	1,096	4,178	1,854	44.4
5B	.674	2,262	575	1,166	4,008	2,102	52.4
5C	.730	2,053	700	1,163	3,921	1,861	47.5
5D	.650	2,645	443	1,142	4,235	1,936	45.7
6A	.497	2,267	285	821	3,378	1,884	55.8
6B	.589	2,605	500	913	4,023	2,535	63.0
6C	.563	3,132	583	1,054	4,774	2,986	62.5
6D	.650	3,542	776	1,227	5,550	3,153	56.8
6E	.635	3,205	776	1,100	5,086	2,930	57.6
6F	.652	3,020	775	951	4,751	2,646	55.7
6G	.736	2,206	775	804	3,790	2,307	60.9
6H	.776	2,670	1,143	800	4,618	2,284	49.5
6I	.673	1,963	568	726	3,262	1,893	58.0
7A	.444	2,291	169	1,072	3,537	1,939	54.8
7B	.451	2,995	283	1,264	4,547	2,433	53.5
7C	.485	3,444	399	1,436	5,286	3,001	56.8
7D	.524	2,957	399	1,344	4,705	2,667	56.7
7E	.562	2,229	399	1,154	3,787	2,158	57.0
7F	.529	2,043	283	1,004	3,335	1,789	53.6
7G	.592	2,465	519	1,238	4,227	2,422	57.3
7H	.403	2,474	169	1,164	3,812	2,034	53.4
8A	.338	2,656	114	1,100	3,875	2,065	53.3
8B	.326	2,119	114	1,043	3,281	1,936	59.0
8C	.377	2,572	223	1,223	4,023	2,482	61.7
8D	.438	3,039	342	1,413	4,799	2,920	60.8
8E	.319	2,412	114	1,203	3,734	2,173	58.2
8F	.391	2,649	223	1,253	4,130	2,406	58.3
8G	.451	2,893	342	1,331	4,571	2,647	57.9
8H	.344	3,353	223	1,497	5,080	2,976	58.6
11A	.462	4,769	316	1,732	6,824	3,581	52.5
11C	.357	3,540	232	1,579	5,358	3,288	61.4
11D	.286	2,812	177	1,440	4,435	2,897	65.3
11E	.389	3,434	232	1,503	5,174	3,068	59.3
11F	.577	2,976	522	1,389	4,892	2,696	55.1
11G	.565	2,739	522	1,397	4,663	2,693	57.8
11H	.587	3,374	574	1,522	5,475	2,972	54.3
11I	.587	4,134	701	1,702	6,544	3,438	52.5
11J	.436	2,246	229	1,146	3,626	2,117	58.4
11K	.445	2,596	266	1,216	4,083	2,304	56.4
11L	.483	2,820	304	1,280	4,409	2,461	55.8
11M	.632	2,404	700	1,442	4,553	2,682	58.9

1/ Calculated from literature reference (1, 3, 4).
2/ Includes sensible heat in heating gas and air to retort, averaging 5-7 M B.t.u.

TABLE 4. - Typical heat and material balance

(Basis: 1 hr. gross heat above 60° F. Run 3 G

	Temp., °F.	Lb. moles	Pounds	M B.t.u.	B.t.u. percent
In:					
Natural lignite as charged, potential heat....	60		539	3,741	67.5
Process steam, total heat....................	240	8.33	150	170	3.0
Heating gas, potential heat..................	81	14.05	218	1,623	29.3
Heating gas, sensible heat...................	81	-	-	4	.1
Air to retort................................	80	34.74	1,007	3	.1
Total..................................			1,914	5,541	100.0
Out:					
CO_2..	665	4.45	196	-	-
CO...	665	7.90	221	-	-
H_2...	665	17.24	35	-	-
Ill..	665	.09	4	-	-
CH_4..	665	1.09	17	-	-
C_2H_6..	665	.03	1	-	-
N_2...	665	.31	9	-	-
Subtotal...............................	-	31.11	483	-	-
Make gas, potential heat.....................	665	-	-	3,594	64.9
Make gas, sensible heat......................	665	-	-	145	2.6
Undecomposed steam, total heat...............	665	6.06	109	146	2.6
Subtotal...............................	-	-	592	3,885	70.1
Char and dust, potential heat................	560	-	93	1,059	19.1
Char and dust, sensible heat.................	560	-	-	15	.3
Stack gases, total heat......................	645	-	1,225	277	5.0
CO_2 lost.....................................	-	-	2	-	-
Radiation and unaccounted for losses.........	-	-	2	305	5.5
Total..................................			1,914	5,541	100.0

DISCUSSION OF RESULTS

The variation of the thermal requirements with operating conditions is significant in the design and operation of a lignite-gasification plant. As indicated by figure 2 and equation (B), the heat requirements per standard cubic foot of wet gas produced vary widely with the H_2-CO ratio. Under the prevailing operating conditions, this variation ranges from approximately 115 to 35 B.t.u. corresponding to the minimum and maximum H_2-CO ratios of 2 and 9, respectively.

In contrast to this, the heat requirements, on a basis of a standard cubic foot of dry gas produced, vary only moderately with the H_2-CO ratio. Equation (C) indicates that the B.t.u. required per standard cubic foot of dry gas produced range only from 135 to 107 between the H_2-CO ratios of 2 and 9. Therefore, it may be concluded that in spite of the wide variations in the experimental operating conditions for gasifying lignite, the thermal requirements, on a basis of the dry volume of gas produced, are fixed within narrow limits.

The cold thermal efficiency of the lignite-gasification unit is necessarily low. This is due to the various heat losses that occur, such as: Losses in sensible heat in the gas produced; losses in both potential and sensible heat in the char and dust; losses in sensible heat in the stack gases; heat losses in the undecomposed steam, and radiation losses. The potential heat of the char, which is not utilized in the pilot plant at present, represents approximately 20 percent of the total heat output.

If the char were effectively utilized and included as useful heat, it would raise the maximum efficiency of the gasification unit under prevailing operating conditions to approximately 80 percent.

As indicated by figure 3, the efficiency decreases with increasing fractions of undecomposed steam. As the fraction of undecomposed steam approaches 1, the efficiency should approach zero, because less and less gas will be generated. However, under the prevailing operating conditions, the efficiency ranges only from 45 to 65 percent.

CONCLUSIONS

1. In spite of the wide variations in the experimental operating conditions for gasifying lignite, the thermal requirements, on a basis of the dry volume of gas produced, are fixed within narrow limits. The B.t.u. required per standard cubic foot of dry gas produced vary from 137 to 107 between the H_2-CO ratios of 2 and 9, respectively.

2. The highest thermal efficiencies attained in the lignite-gasification pilot plant occur at the lower H_2-CO ratios.

3. Under the prevailing operating conditions, the cold thermal efficiency of the lignite-gasification unit ranges from 45 to 65 percent. However, if the potential heat of the char produced were effectively utilized and included as useful heat, the maximum efficiency would be raised to approximately 80 percent.

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